Development of a Superconducting Magnet System for a Helicon Plasma Thruster

John Vitucci
Advisor: Dr. Raymond Sedwick
NASA Space Technology Research Fellow
University of Maryland, College Park
Space Power and Propulsion Lab
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Outline

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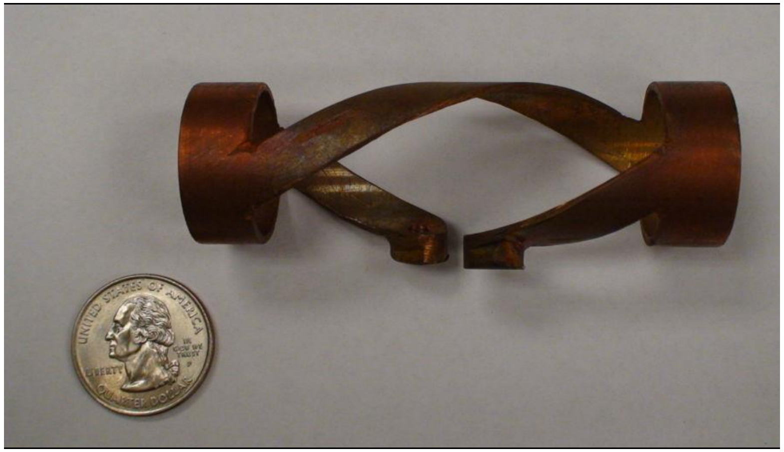
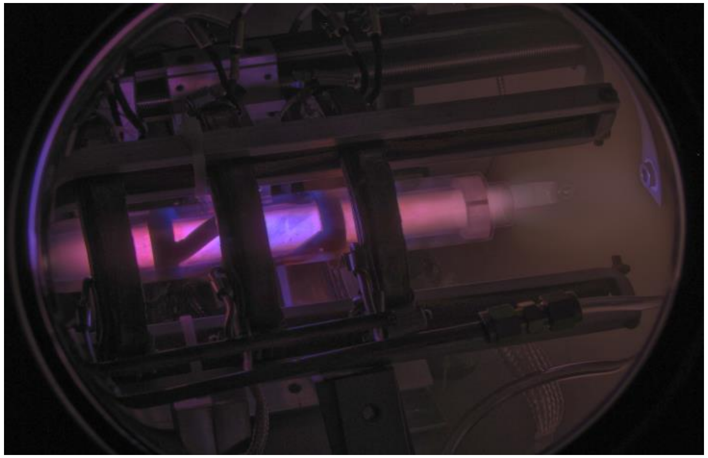
  - Motivation
  - Previous Designs
- Superconducting Helicon Thruster (SHT)
  - Superconducting Magnet Subsystem
  - Thermal Management Subsystem
- Conclusion and Future Work

Introduction: Helicon Thruster

- Helicon waves generated with helical RF antennas
  - Frequency 13.56 MHz (or a harmonic/sub-harmonic)
- Antenna current induces time varying magnetic field
  - Resulting in curling electric field according to Maxwell's equations
- Electric field accelerates free electrons until ionization energy reached
- Critical density of electrons occurs causing plasma ignition from electron avalanche[1]



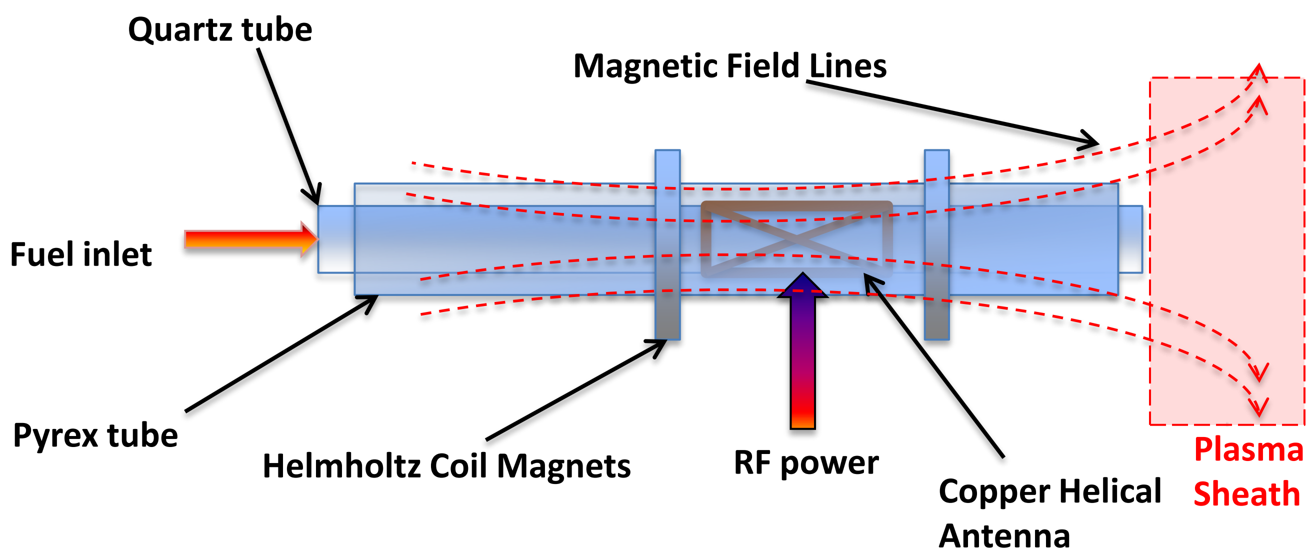
Single turn, half-wavelength helical RF antenna for helicon plasma generation. Photo courtesy M. DeMaio[5].



SPPL Helicon thruster operating at 300W RF and axial field strength approximately 200 G . Photo courtesy A.J. Faust.

Introduction: Helicon Thruster

- Requires an externally applied, axial magnetic field to[2]:
  - Support the propagation of the helicon wave
  - Improve plasma confinement
  - Support the formation of the naturally occurring acceleration mechanism[3]
- Magnetic field strength directly determines the plasma density[4]
  - Little evidence that it contributes to ion acceleration[5]
- Depending on power input, thruster operates at three coupling modes[6]
  - Capacitive
  - Inductive
  - Helicon



SPPL Helicon Schematic. Photo courtesy A.J. Faust.

Introduction: SHT - Motivation

- Largest power sink occurs at the plasma boundary across plasma sheath[7]
- Impose two conditions on the magnetic field:
  - Axial uniformity to support helicon wave propagation
  - Convergence upstream to improve plasma confinement
- Superconductors to manipulate magnetic field via Meissner effect
- Straight forward with low temperature type-I superconductor
  - Exhibit perfect diamagnetism and completely expel magnetic flux (+)
  - Lower temperature impractical due to cooling system requirements (-)
- High temperature type-II superconductors (HTS)
  - Can be cooled with liquid nitrogen (+)
  - Allows partial penetration of magnetic flux due to mixed/vortex state[8] (-)
- Impose two conditions on thermal management subsystem:
  - Maintain cryogenic temperatures for HTS in closed loop system
  - Intercept heat generated by plasma and radiate away

Introduction: SHT – Previous Designs

"Concept Car"

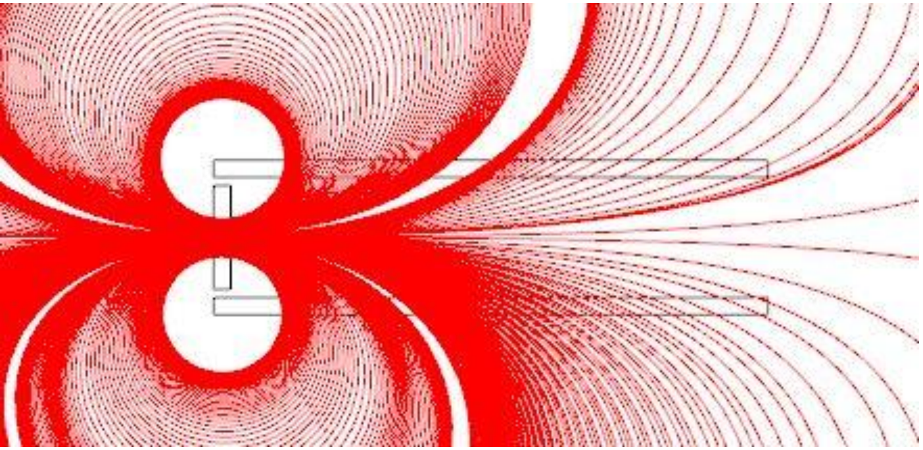
- Superconductor capped by permanent disk magnet

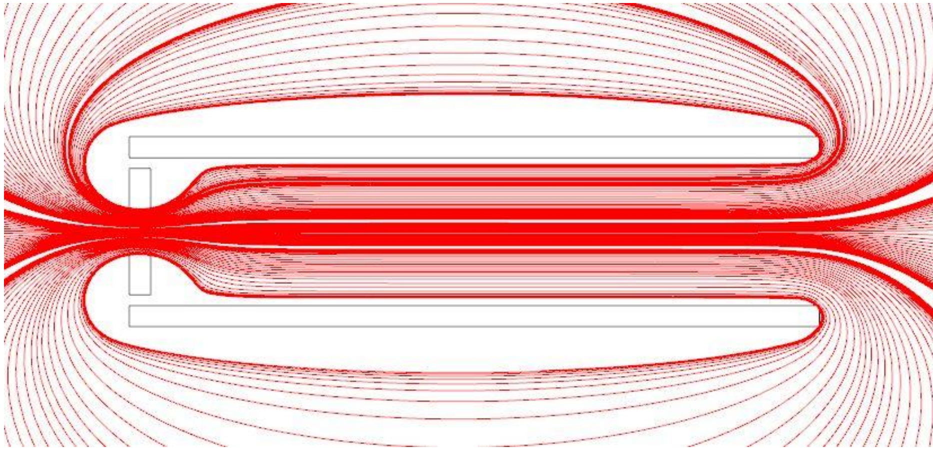
Pros:

- Generates correct shape
- Simplistic design

Cons:

- Magnetic flux locked in by superconductor (Type-II)
- Disc magnet eliminates gas inlet





Introduction: SHT – Previous Designs

"2nd Gen"

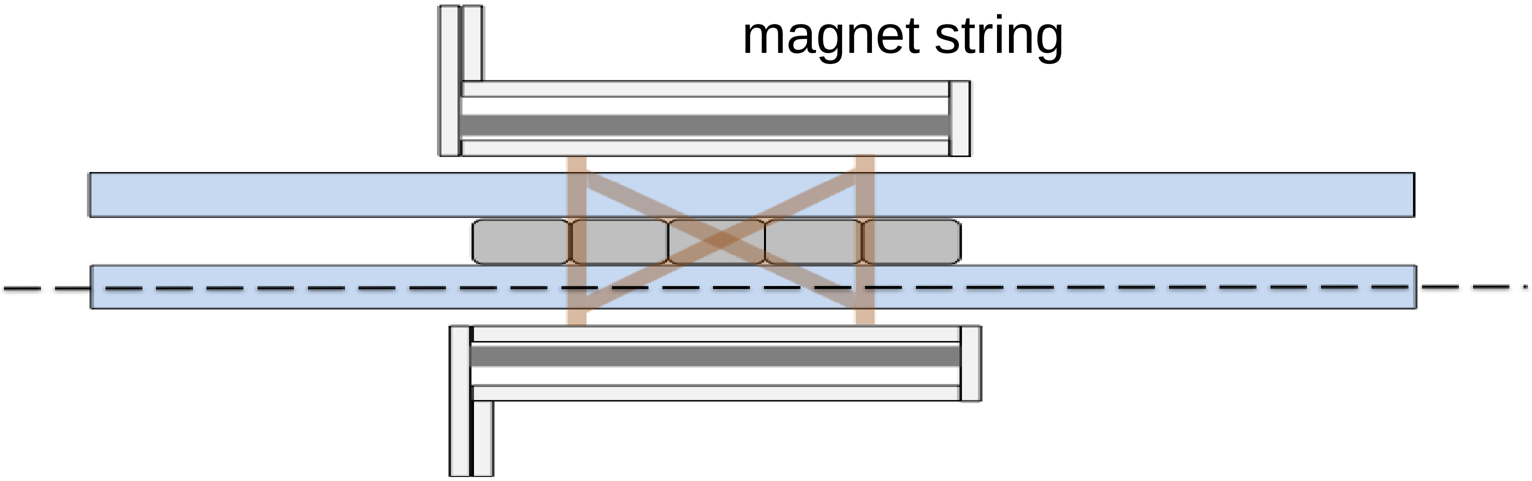
- Annular tube with retractable permanent magnet core

Pros:

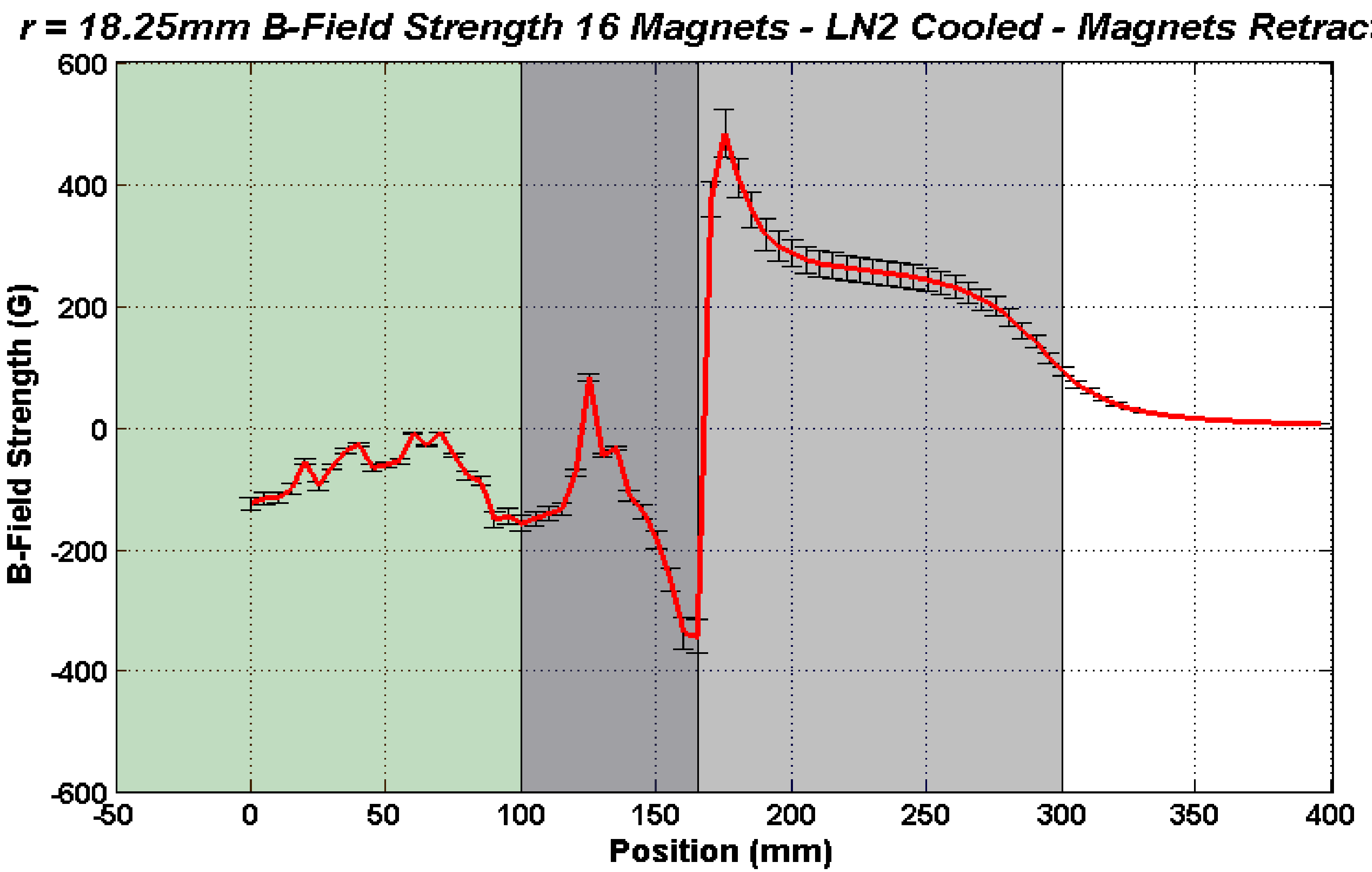
- Eliminates lock-in problem
- Allows for gas inlet

Cons:

- Annular design increases power loss area
- Does not provide uniform field within and downstream of antenna
- Requires actuation of permanent magnet string

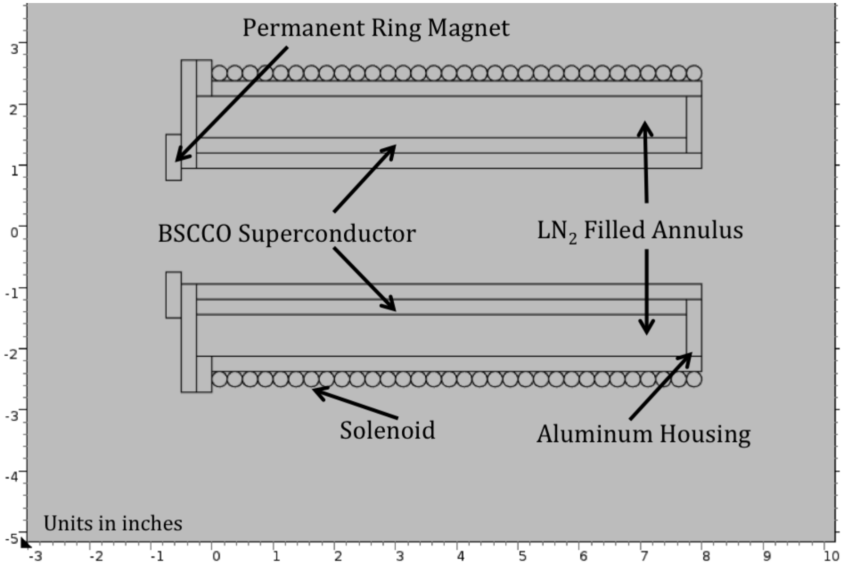


Introduction: SHT – Previous Designs



SHT: Superconducting Magnet Subsystem

- Magnetic field from permanent magnet and solenoid combination
- Solenoid is used to generate an axially uniform magnetic field
- Upstream convergence produced with a permanent ring magnet
- Liquid nitrogen pumped into the annulus of aluminum housing
- Solenoid powered off once the critical temperature of HTS is reached
- Current induced in the superconductor according to Lenz's Law



SHT Schematic in COMSOL MultiPhysics.

Superconductor housing and solenoid.

SHT: Superconducting Magnet Subsystem

- Magnitude of induced current in solenoid is *nI*
- Assume superconductor acts as a solenoid itself with equal length, *L*
- Axial magnetic field strength identical to that of solenoid (Ampere's Law)

$$B = \frac{\mu_0 n I}{L}$$

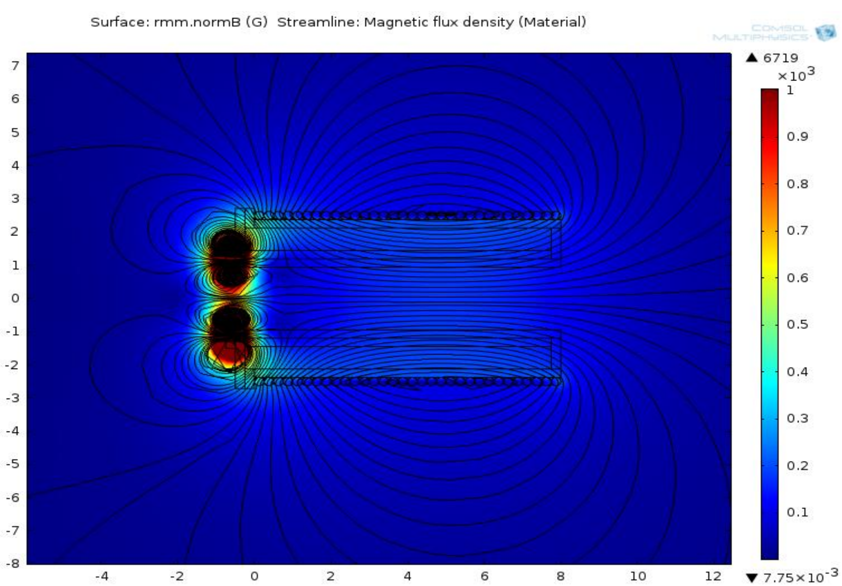
B: Axial Magnetic Field Strength (G)
μ_0: Permeability of Free Space
n: Number of Solenoid Turns
I: Current through Solenoid (A)
L: Solenoid Length (m)

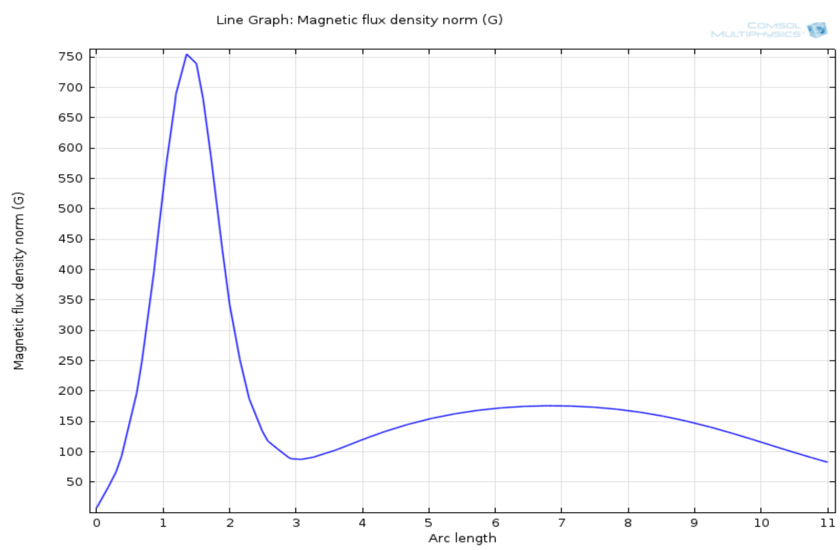
- Induced current (*nI*) maintains magnetic field without continuous power
- Tested with smaller (0.85" ID) superconductor and Helmholtz coil
  - Coil produced 65 G ± 4 G and was maintained by solenoid
- Modeled magnet subsystem in COMSOL MultiPhysics
- Hardware currently in development for comparison with model

SHT: Superconducting Magnet Subsystem

Computation Results: $T > T_C$

- Magnet mirror configuration observed upstream
- Field is not uniform axially due to permanent ring magnet

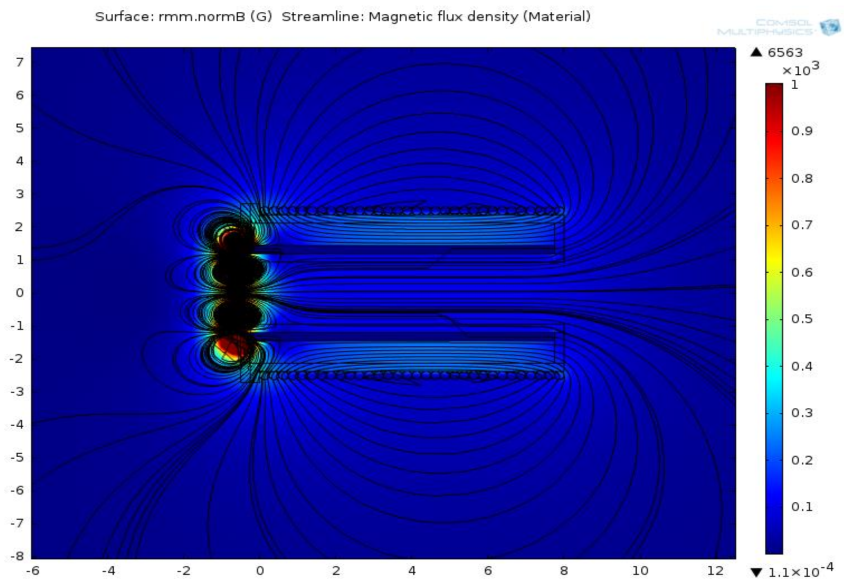


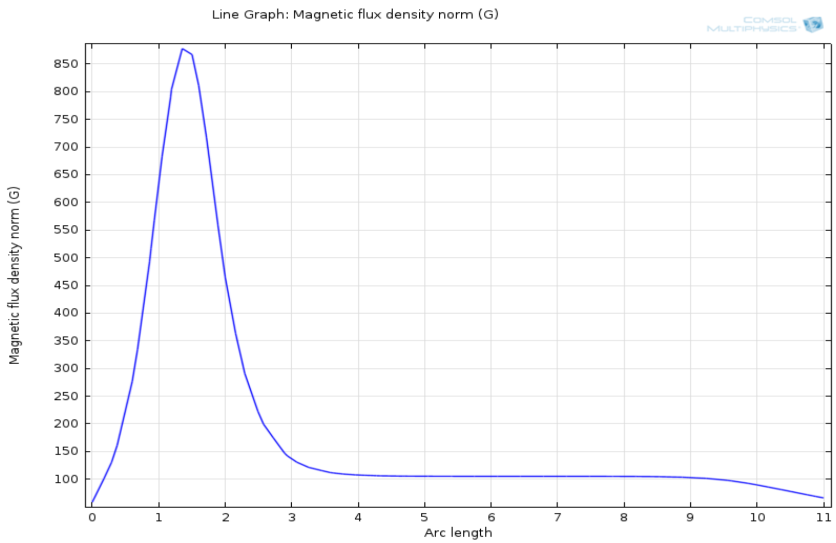


SHT: Superconducting Magnet Subsystem

Computation Results: $T < T_C$

- Magnet mirror configuration maintained and larger in magnitude
- Axial magnetic field has become more uniform





SHT: Thermal Management Subsystem

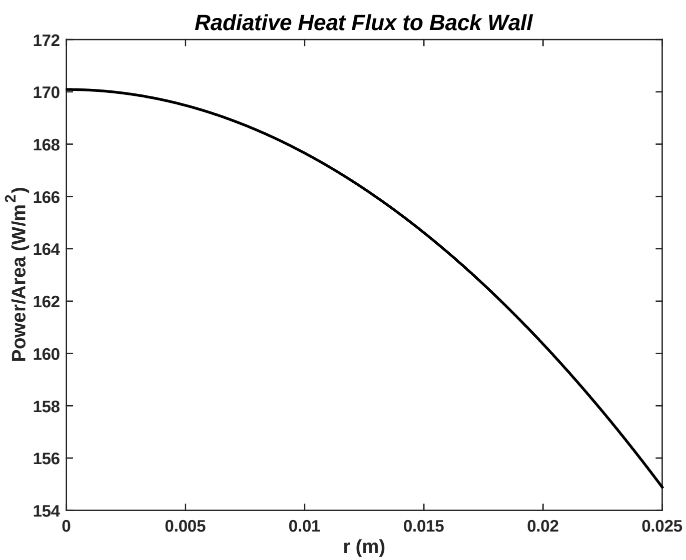
- Power generated by plasma must be intercepted and radiated away to maintain cryogenic temperatures in closed-loop system

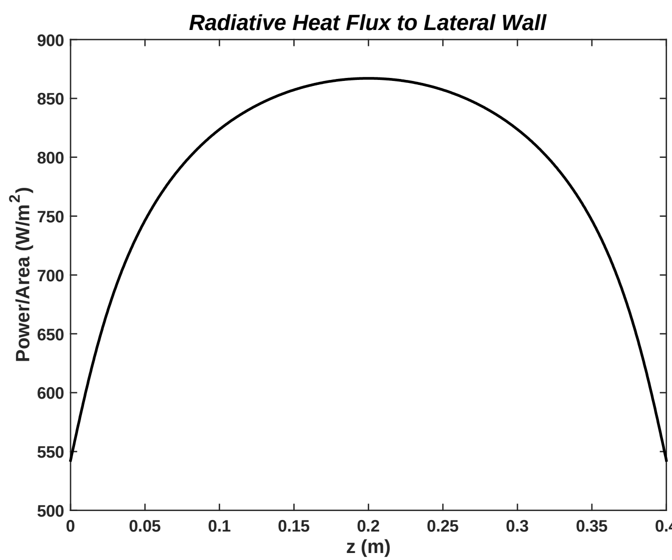
Radiated Power: $$\dot{P}_{rad}(z,r) = \left(E'_{ion} - E_{ion}\right) n n_n R_{ion}$$ [W/m³]

Conducted Power: $$q_r(z) = \left(2 + \frac{1}{2}\ln\left(\frac{m_i}{2\pi m_e}\right)\right) kT_e n_s(z) c_s$$ [W/m²]

L = 40 cm
R = 2.5 cm
Te = 5 eV

- Calculate radiative heat flux to each wall then conducted power to lateral wall
  - Assume no conducted power upstream due to confinement

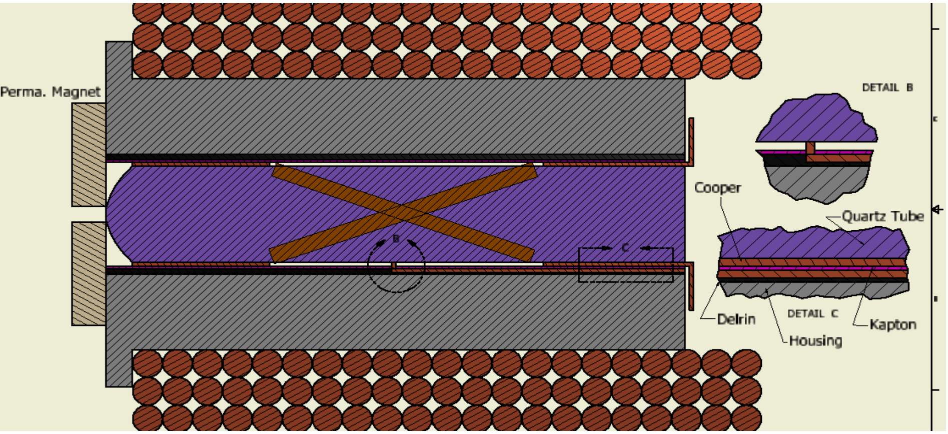


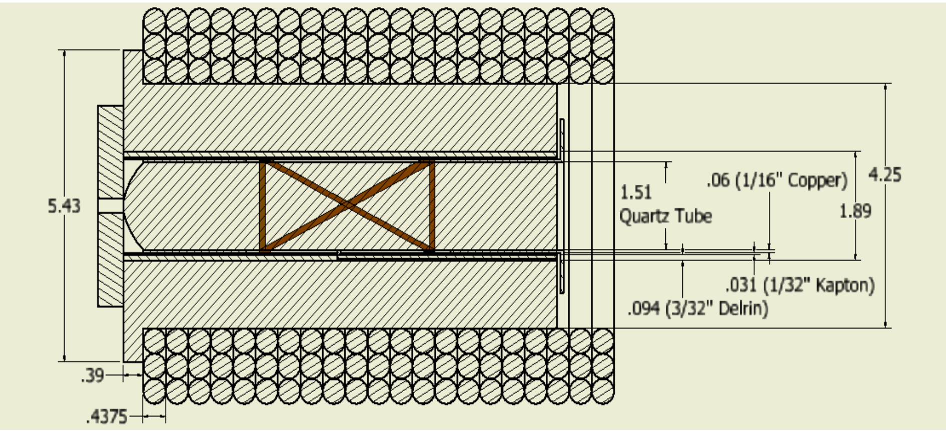


- Integrate over area
  - P_{BW} = 0.32 W
  - P_{LW} = 50 W
  - P_{cond} = 3.9 kW
  - P_{tot} ~ 4 kW

SHT: Thermal Management Subsystem

- Utilize three insulating layers between quartz and superconductor housing
  - Conformal copper layer to intercept power to walls
  - Kapton layer to electrically insulate power leads to antenna
  - Delrin layer to thermally insulate housing (maintain cryogenic temperatures)
- Conformal copper layer attached to copper disk at exit plane to radiate heat
- Can use excess heat to evaporate water in water vapor propellant applications
- Use power source calculations to calculate heat transfer in system
  - MATLAB simulation using heat transfer equation
  - Determine appropriate layer thicknesses to properly insulate system

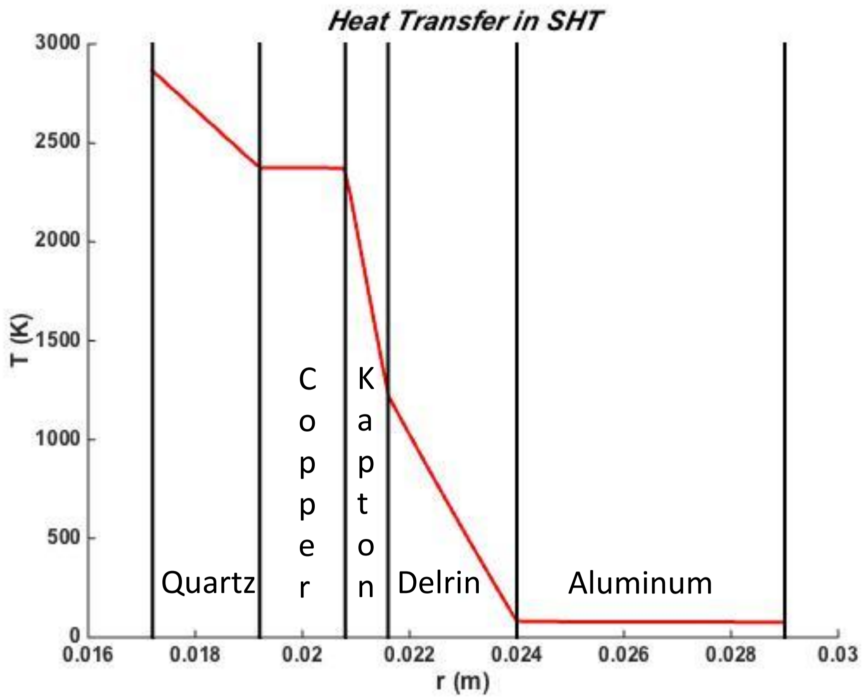




SHT: Thermal Management Subsystem

$$\frac{\partial T}{\partial t} = \frac{k}{c_p \rho}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right] + \frac{\dot{q}}{c_p \rho}$$

- Solve heat transfer equation in one dimension
  - Steady State
- Quartz layer
  - P_{cond} = 3.9 kW
- Copper layer
  - P_{rad} = 100 W
- Boundary Conditions:
  - $T(r = OR_{Al}) = 77$ K
  - $q(r = IR_{Qu}) = P_{cond}/A_{qu} = -k\,(dT/dr)|_{r=IR\_Qu}$



Liquid nitrogen region maintains cryogenic temperatures.

Conclusion & Future Work

- A superconducting helicon plasma system is presented
  - Superconducting magnet subsystem satisfies magnetic field requirements
  - Thermal management subsystem to address heat transfer/insulation
- Each subsystem will be constructed and compared with the computational models
- Complete system will be integrated into helicon thruster setup at UMD SPPL
  - Compare with baseline helicon plasma thruster performance

Acknowledgements

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Thank You

Questions?